FIBER REINFORCED PLASTIC PIPE AND POWER TRANSMISSION SHAFT EMPLOYING THE SAME

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a fiber reinforced plastic pipe for use such as with a propeller shaft or a drive shaft which constitutes part of the power transmission system of a vehicle. The present invention also relates to a power transmission shaft incorporating the fiber reinforced plastic pipe.

2. Description of the Related Art

Those shafts that constitute the power transmission system of a vehicle include a propeller shaft for transmitting power from the gearbox to the reduction gear, and a drive shaft for coupling the engine and the hub joint. Any of the shafts is provided at the ends thereof with universal joints, and constructed to respond to variations in length and angle resulting from changes in relative position between the gearbox and the reduction gear or between the engine and the hub joint.

Fig. 8 is a view illustrating an example of a power transmission shaft, showing the overall view of a propeller shaft 1. The propeller shaft 1 is provided with stub

shafts 3 and 4, a type of metal joint elements, which are jointed to the both ends of an intermediate shaft 2. The stub shafts 3 and 4 mate with the joint inner ring of constant velocity joints 5 and 6 by means of splines or serrations. Figs. 9a and 9b are views illustrating another example of a power transmission shaft, showing an intermediate shaft of the drive shaft. Fig. 9a illustrates an intermediate shaft 7 provided with no dynamic damper, and Fig. 9b illustrates an intermediate shaft 8 provided with a dynamic damper 9 for preventing vibrations.

It has been a conventional process to employ hollow or solid steel shafts for the intermediate shaft 2 of the propeller shaft 1 and the intermediate shafts 7, 8 of the drive shaft. From the viewpoint of flexural rigidity, an elongated intermediate shaft that constitutes the power transmission shaft needs to be provided at the intermediate portion thereof with a support bearing or a dynamic damper for preventing vibrations. Accordingly, improvements have been required for the shaft in weight and cost, and thus it has been difficult to provide an elongated shaft.

In view of these improvements, it has been suggested to employ a hollow pipe formed of a fiber reinforced plastic (hereinafter referred to as the FRP pipe) and having a high flexural rigidity in combination with a metal pipe. This improves the flexural rigidity of the

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intermediate shaft to eliminate the support bearing or the

dynamic damper for preventing vibrations at the

intermediate portion, thereby reducing the shaft in weight

and cost and making it possible to provide an elongated

5   shaft.

For example, the FRP pipe can be reduced in thickness

and increased in diameter by pultrusion process. By

pultrusion process, a plurality of fiber bundles are spun

and hardened continuously while being aligned in the

10   longitudinal direction, thereby making it possible to

efficiently manufacture a pipe-shaped molded product having

a uniform cross-section. To combine the FRP pipe obtained

by the pultrusion process with a metal pipe, such a typical

technique has been processed in which the FRP pipe is

15   mechanically press-fitted into the metal pipe.

That is, it is conceivable that the FRP pipe is

inserted into the metal pipe and then the outer

circumference of the metal pipe is reduced in diameter by

plastic-working in order to fix the FRP pipe to the metal

20   pipe. Alternatively, to fix the FRP pipe to the metal pipe,

an adhesive can be injected into the gap between the metal

pipe and the FRP pipe. However, in a case where the FRP

pipe and the metal pipe are formed in the shape of a simple

cylinder and have a tolerance of size, respectively, it is

25   necessary to match the dimensions with each other to

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control subtle press-fitting or press-fit pressures in the process, thereby making the assembly extremely complicated.

In contrast to this, using an FRP pipe having a slit in the axial direction would eliminate the aforementioned subtle matching for press-fitting and reduce the press-fit pressure. In other words, the FRP pipe can be reduced in diameter in the circumferential direction when the FRP pipe is incorporated into the metal pipe. This allows for a plastic deformation by the width of the slit, thereby making the assembly considerably easier in comparison with a case where a cylindrical pipe having no slit is press-fitted into the metal pipe.

Furthermore, suppose that the FRP pipe with a slit is formed to have an outer diameter greater than the inner diameter of the metal pipe, so that the apparent outer diameter of the FRP pipe is less than the inner diameter of the metal pipe when the FRP pipe is elastically deformed by the width of the slit in the circumferential direction. In this case, after the assembly, the FRP pipe will expand inside the metal pipe back to the original outer diameter provided upon its formation. This elastic recovery force serves to press the FRP pipe against the metal pipe, thereby making it possible to securely fix the FRP pipe to the metal pipe.

However, in a case where upon inserting the FRP pipe

into the metal pipe, the FRP pipe is so damaged due to
cracks as not to make use of its practical performance, the
effectiveness of the aforementioned various techniques is
ruined, making it difficult to employ the FRP pipe for use
5   with the power transmission shaft.

　　　To form the FRP pipe by pultrusion process, it is a
common process to draw all fiber bundles being aligned in
the longitudinal direction of the pipe in order to make
full use of the mechanical properties of the fibers that
10   are used for the FRP pipe. However, an FRP pipe which is
reduced in thickness and increased in diameter by
pultrusion process makes such a problem noticeable that the
FRP pipe is sensitive to crushing force exerted from the
circumference, thereby causing longitudinal or other cracks
15   to readily develop.

　　　Furthermore, when the FRP pipe with a slit is
elastically deformed by the width of the slit and thus
reduced in diameter, the maximum tensile stress occurs on
an outer surface of the pipe, the outer surface being
20   opposite to the slit with respect to the center of the pipe.
This tensile stress increases in proportion to the width of
the slit of the FRP pipe, thereby increasing the
possibility of occurrence of cracks. In particular,
reinforcement fibers spun being aligned in the longitudinal
25   direction of the pipe may easily raise the problem that

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longitudinal or other cracks are also caused by the stress

developed due to thermal expansion in addition to the

stress caused by an external force.

5   SUMMARY OF THE INVENTION

It is therefore an object of the present invention to

prevent an FRP pipe from being damaged and make full use of

its practical performance, when the FRP pipe reduced in

thickness and increased in diameter by pultrusion process

10   is reduced in diameter in the circumferential direction and

then inserted into a metal pipe. The present invention has

the following features.

1. According to a first aspect of the present

invention, an FRP pipe reduced in thickness and increased

15   in diameter by pultrusion process, comprises a fiber bundle

spun and aligned in the longitudinal direction, and

circumferential reinforced fiber sheet provided at least

either on an outer surface layer or on an inner surface

layer. In this invention, the fiber bundle is spun and

20   aligned in the longitudinal direction of the pipe, thereby

allowing for making full use of the mechanical properties

of the fibers for use with the FRP pipe. The FRP pipe is

also provided with the circumferential reinforced fiber

sheet at least on either the outer surface layer or the

25   inner surface layer of the FRP pipe, thereby making it

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possible to prevent tensile strain from developing in the

circumferential direction of the pipe. Consequently, this

makes the pipe robust against the crushing force exerted

from the circumference and less prone to longitudinal

5   cracks or other cracks.

2. According to a second aspect of the present

invention, an FRP pipe reduced in thickness and increased

in diameter by pultrusion process, comprises a fiber bundle

spun and aligned in the longitudinal direction, and

10   circumferential reinforced fiber sheet provided at least

either on an outer surface layer or on an inner surface

layer, and has a slit, capable of being reduced in diameter

along the circumference, provided in the longitudinal

direction. In this arrangement, the fiber reinforced

15   plastic pipe can be inserted into a metal pipe. In this

invention, upon incorporating the FRP pipe into the metal

pipe, reducing the FRP pipe in diameter in the

circumferential direction makes it possible to elastically

deform the pipe by the width of the slit. This makes the

20   assembly considerably easier in comparison with a case

where a cylindrical pipe with no slit is press-fitted into

the metal pipe. Consequently, it is possible to provide an

FRP pipe which enables to make full use of its practical

performance without damaging the FRP pipe.

25   3. According to a third aspect of the present

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invention, in a power transmission shaft comprising a metal
joint element and a metal pipe jointed to each other, an
FRP pipe is inserted into the metal pipe, the FRP pipe
being reduced in thickness and increased in diameter by

5   pultrusion process, comprising a fiber bundle spun and
aligned in the longitudinal direction, and circumferential
reinforced fiber sheet provided at least either on an outer
surface layer or on an inner surface layer. In this
invention, the FRP pipe having a high flexural rigidity is

10   disposed inside the metal pipe, thereby making it possible
to improve the flexural rigidity of the power transmission
shaft. This allows for eliminating a support bearing at
the intermediate portion or a dynamic damper for preventing
vibrations, thereby reducing the shaft in weight and cost

15   and providing an elongated shaft.

     4. According to a fourth aspect of the present
invention, in a power transmission shaft comprising a metal
joint element and a metal pipe jointed to each other, an
FRP pipe is inserted into the metal pipe, the FRP pipe

20   being reduced in thickness and increased in diameter by
pultrusion process, comprising a fiber bundle spun and
aligned in the longitudinal direction, and circumferential
reinforced fiber sheet provided at least either on an outer
surface layer or on an inner surface layer, and having a

25   slit, capable of being reduced in diameter along the

circumference, provided in the longitudinal direction. In this invention, upon incorporating the FRP pipe into the metal pipe, reducing the FRP pipe in diameter in the circumferential direction makes it possible to elastically deform the pipe by the width of the slit. This makes the assembly considerably easier in comparison with a case where a cylindrical pipe with no slit is press-fitted into the metal pipe.

Consequently, it is possible to employ welding, which is robust and provides for a long-term service reliability, to joint the metal pipe and the joint element together. This allows for using the power transmission shaft for a car equipped with a constant velocity joint. In addition to the use for cars, the power transmission shaft can also be used advantageously for ships, various types of industrial machines, and aircraft.

5. In the FRP pipe, the tensile elasticity of fibers that form the fiber bundle of the FRP pipe is 196GPa or more. This makes it possible to increase the first-order flexural resonance frequency of the FRP pipe. To this end, it is preferable to use PAN-based carbon fibers which have such a tensile elasticity.

6. In the FRP pipe, the tensile elasticity of fibers that form the circumferential reinforced fiber sheet of the FRP pipe is 58.8GPa or more. This makes it easy to prevent

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the tensile strain from developing in the circumferential
direction of the pipe.

7. The FRP pipe is adapted such that the basis weight
(this may be referred to as FAW (Fiber Area Weiht) in this
technical field which means weight per unit area) of the
circumferential reinforced fiber sheet of the FRP pipe is
within the range of 100g/m^2 to 600g/m^2. This facilitates
the continuous formation of the FRP pipe by pultrusion
process.

8. In the FRP pipe, the thickness of the
circumferential reinforced fiber sheet of the FRP pipe is
within the range of 0.05mm to 1.0mm. This facilitates the
continuous formation of the FRP pipe by pultrusion process.

It is preferable to use glass fibers or PAN-based
carbon fibers as the fibers that constitute the
circumferential reinforced fiber sheet of the FRP pipe set
forth in items 6 to 8.

9. In the power transmission shaft, the FRP pipe is
provided with a slit having a width of 0.01% or more and
40% or less of the outer circumference of the FRP pipe in
its natural state. This eliminates the matching of the
outer diameter of the FRP pipe and the inner diameter of
the metal pipe for controlling the subtle press-fitting and
the press-fit pressure in the process. This also makes it
possible to provide a well balanced condition for the high-

speed rotation of the power transmission shaft.

10. In the power transmission shaft, the slit has a bias angle within ± 30 degrees with respect to the axial direction of the FRP pipe. This makes it possible to improve the flexural rigidity of the power transmission shaft.

11. In the power transmission shaft, the value of D_1/D_2 is greater than 1 and 1.3 or less, where D_1 is the outer diameter of the FRP pipe and D_2 is the inner diameter of the metal pipe. In this context, the FRP pipe is so formed as to have an outer diameter that is greater than the inner diameter of the metal pipe, so that the FRP pipe has an apparent outer diameter less than the inner diameter of the metal pipe when having been elastically deformed by the slit width in the circumferential direction. Consequently, after having been incorporated into the metal pipe, the FRP pipe expands attempting to restore its original outer diameter provided upon its formation inside the metal pipe. This makes it possible to fix the FRP pipe to the metal pipe.

12. In the power transmission shaft, the FRP pipe has a layered structure of 20 layers or less. This eliminates complicated preparation for formation, thereby making it possible to improve the mass productivity of the FRP pipe.

13. In the power transmission shaft, the value of

FL/PL is 0.1 or more and 1.0 or less, where PL is the
length of the metal pipe and FL is the length of the FRP
pipe. This makes it possible to ensure the flexural
rigidity of the power transmission shaft.

5   14. In the power transmission shaft, the value of
t_2/t_1 is 0.01 or more and 10 or less, where t_1 is the
thickness of the metal pipe and t_2 is the thickness of the
FRP pipe. This makes it possible to ensure the flexural
rigidity that satisfies the flexural natural frequency of
10 the power transmission shaft.

15. The FRP pipe can be fixed to the metal pipe by
reducing the metal pipe in diameter along the outer
circumference of the metal pipe by means of plastic-working
or by with adhesive, with the FRP pipe being inserted in
15 the metal pipe. In the latter case where adhesive is used,
a recessed portion for accommodating adhesive may be
provided on the outer circumference of the FRP pipe or only
on the inner circumference of the metal pipe, or on both
the outer circumference of the FRP pipe and the inner
20 circumference of the metal pipe. This makes it possible to
positively form an adhesive layer between the outer
circumference of the FRP pipe and the inner circumference
of the metal pipe after the pipes have been assembled.

The nature, principle, and utility of the invention
25 will become more apparent from the following detailed

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description when read in conjunction with the accompanying

drawings in which like parts are designated by like

reference numerals or characters.

5   BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

Fig. 1a is a perspective view illustrating a metal

pipe, and Fig. 1b is a perspective view illustrating an FRP

10   pipe;

Fig. 2a is a perspective view illustrating a step in

which an FRP pipe is press-fitted into a metal pipe, Fig.

2b is a perspective view illustrating a metal pipe in which

an FRP pipe has been press-fitted, and Fig. 2c is a

15   perspective view illustrating a metal pipe both ends of

which have been spun;

Fig. 3a is a perspective view illustrating an FRP

pipe provided with a slit,

Fig. 3b is a perspective view illustrating a step in which

20   an FRP pipe with a slit is press-fitted into a metal pipe,

Fig. 3c is a perspective view illustrating a metal pipe in

which an FRP pipe with a slit has been press-fitted, Fig.

3d is an end view of an FRP pipe with a slit in a natural

state, and Fig. 3e is an end view of an FRP pipe with a

25   slit, the pipe being reduced in diameter;

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Fig. 4a is a perspective view illustrating an FRP pipe with a slit formed at a bias angle, Fig. 4b is a perspective view illustrating a step in which an FRP pipe with a slit formed at a bias angle is press-fitted into a

5   metal pipe, and Fig. 4c is a perspective view illustrating a metal pipe in which an FRP pipe with a slit formed at a bias angle has been press-fitted;

Fig. 5a is a perspective view illustrating an FRP pipe provided with axial grooves and a slit, Fig. 5b is a

10   perspective view illustrating a step in which an FRP pipe with axial grooves and a slit is press-fitted into a metal pipe, and Fig. 5c is a perspective view illustrating a metal pipe in which an FRP pipe with axial grooves and a slit has been press-fitted;

15   Fig. 6a is a perspective view illustrating an FRP pipe with circumferential grooves and a slit, and Fig. 6b is a perspective view illustrating an FRP pipe with a slit and recessed portions;

Fig. 7a is a perspective view illustrating a metal

20   pipe having circumferential grooves formed on the inner circumferential surface, Fig. 7b is a longitudinal sectional view illustrating the metal pipe of Fig. 7a, Fig. 7c is a perspective view illustrating a metal pipe in which an FRP pipe has been inserted, and Fig. 7d is a

25   longitudinal sectional view of Fig. 7c;

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Fig. 8 is an external view illustrating an example of a propeller shaft; and

Fig. 9a is a front view illustrating an example of an intermediate shaft for use with a drive shaft, and Fig. 9b

5   is a front view illustrating another example of an intermediate shaft for use with a drive shaft.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10   A metal pipe 11 shown in Fig. 1a is used in combination with an FRP pipe 12 shown in Fig. 1b. As shown in Figs. 2a to 2c, the FRP pipe 12, which has been reduced in thickness and increased in diameter by pultrusion process, is inserted into the metal pipe 11, for use with a

15   power transmission shaft as its intermediate shaft 2, 7, and 8 (see Figs. 8 and 9). The FRP pipe 12 having a high flexural rigidity is disposed inside the metal pipe 11, thereby making it possible to improve the flexural rigidity of the power transmission shaft. This allows for

20   eliminating a support bearing at the intermediate portion or a dynamic damper for preventing vibrations, thereby reducing the shaft in weight and cost and providing an elongated shaft.

In addition to this, the FRP pipe 12 is inserted into

25   the metal pipe 11 to form the power transmission shaft.

This makes it possible to provide the shaft with high

durability sufficiently enough to withstand a large

shearing force for the transmission of power because the

shaft has a metallic joint portion at the end portion

5   thereof available for jointing with a joint element. That

is, it is possible to employ a joint method, perfect in

reliability, such as welding or friction welding for

coupling between the metal pipe 11 and the joint element.

This makes it possible to perfectly prevent circumferential

10   sliding or axial dislodging, thereby providing the joint

portion with long-term reliability.

Furthermore, it is also possible to stack FRP layers,

in combination, of the FRP pipe 12 inserted into the metal

pipe 11, the FRP layers having the fibers disposed at

15   angles of 0 degree and ±45 degrees to the axial direction

of the metal pipe 11. This makes it possible to control

flexural rigidity and torsional rigidity. It is also

acceptable to control the flexural rigidity, torsional

rigidity, and resistance to buckling by means of the length

20   of the FRP pipe 12 inserted into the metal pipe 11, the

thickness ratio between the metal pipe 11 and the FRP pipe

12, the elasticity of the fibers used or the like.

As shown in Fig. 2c, to fix the FRP pipe 12 to the

metal pipe 11, the FRP pipe 12 is incorporated into the

25   metal pipe 11. Then, for example, the metal pipe 11 is

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spun to be deformed plastically and reduced in diameter, thereby fixing the FRP pipe 12 to the metal pipe 11 (the portion reduced in diameter is indicated by reference numeral 13 in the figure).

As shown in Figs. 3a to 3c, it is also possible to use an FRP pipe 12a having a slit 14 formed in the axial direction. Consider a case where the FRP pipe 12a having the slit 14 formed in the axial direction is incorporated into the metal pipe 11, while being reduced in diameter. In this case, it is easy to elastically deform the FRP pipe 12a by the width W of the slit in the circumferential direction (see Figs. 3d and 3e). Accordingly, the assembly of the FRP pipe 12a is drastically made easier in comparison with the press-fitting of an FRP pipe having no slit.

That is, since the outer diameter of the FRP pipe and the inner diameter of the metal pipe have their respective tolerances of size, it is necessary to match the dimensions with each other to control press-fit pressures in the process for the pipes each having a simple cylindrical shape. In contrast to this, the FRP pipe 12a having the slit 14 eliminates the aforementioned matching and permits a reduced press-fit pressure.

The slit width W is set to the range from 0.01% to 40% of the outer circumference of the FRP pipe in its

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natural state. A slit width W less than 0.01% of the outer circumference of the FRP pipe may require matching even when the FRP pipe is elastically deformed in the circumferential direction. On the contrary, a slit width W greater than 40% of the outer circumference of the FRP pipe may increase the amount of imbalance in rotation, thereby causing a problem of runouts at high speed rotations.

The cross-sectional shape of the slit 14 is not limited to any particular one, but will be advantageous if the shape can be continuously formed by pultrusion process. In addition, to form the slit 14, the FRP pipe 12 may be first formed in the shape of a cylinder and then provided with the slit 14 by cutting.

As shown in Figs. 4a to 4c, to form a slit continuously by pultrusion process, it is possible to provide an FRP pipe 12b with a slit 14a formed at a bias angle θ with respect to the axial direction. In this case, the bias angle θ is preferably within ±30 degrees. A slit 14a having a bias angle θ greater than 30 degrees causes the tow to be aligned parallel to that direction. Accordingly, this would make it difficult to improve the flexural rigidity of the power transmission shaft that has incorporated an FRP pipe of fibers having a high elasticity.

The FRP pipe 12 having the slit 14 is so formed as to have an outer diameter that is greater than the inner

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diameter of the metal pipe 11, so that the FRP pipe 12 has

an apparent outer diameter less than the inner diameter of

the metal pipe 11 when having been elastically deformed

(reduced in diameter) by the slit width W in the

5   circumferential direction. In this case, it is preferable

that the value of D_1/D_2 is greater than 1 and less than or

equal to 1.3, where D_1 is the outer diameter of the FRP

pipe 12 having the slit 14 (see Fig. 3d) and D_2 is the

inner diameter of the metal pipe 11 (see Fig. 1a).

10   With the value of D_1/D_2 being less than or equal to 1,

the outer diameter of the FRP pipe 12 having the slit 14 is

not greater than the inner diameter of the metal pipe 11,

leaving a gap therebetween. On the contrary, with the

value of D_1/D_2 being greater than 1.3, a deformation caused

15 by a reduction in diameter of the FRP pipe 12 would be

beyond the elastic deformation region in some cases,

thereby raising a problem of cracks.

        After having been incorporated into the metal pipe 11,

the FRP pipe 12 is to expand therein to restore its

20 original outer diameter given upon its formation. This

force acts to press the outer circumference of the FRP pipe

12 against the inner circumference of the metal pipe 11,

thereby causing the FRP pipe 12 to be fixed therein. This

fixing force is advantageous when the metal pipe 11 is

25 deformed by spinning or by means of adhesive.

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Upon being reduced in thickness and increased in diameter by pultrusion process, the FRP pipe 12 is spun to align its fiber bundles in the longitudinal direction of the FRP pipe 12 and provided with circumferential

5   reinforced fiber sheet 15 on the outer and inner surface layers of the FRP pipe 12 (see Fig. 1b and other figures). The fiber bundles are spun and aligned in the longitudinal direction of the pipe, thereby allowing for making full use of the mechanical properties of the fibers used for the FRP

10   pipe 12 at maximum efficiency. In addition to this, the circumferential reinforced fiber sheet 15 is provided on the outer and inner surface layers of the FRP pipe 12, thereby making it possible to prevent tensile strain of the pipe from developing in the circumferential direction.

15   Upon being reduced in thickness and increased in diameter by pultrusion process, the fibers are impregnated with a non-hardened matrix resin and then hardened continuously while those multiple tows are being overwound, thereby making it possible to efficiently manufacture a

20   pipe-shaped molded product having a uniform cross-section. The FRP pipe 12 can be formed in advance by sheet wrapping. However, the pultrusion process may be used to significantly reduce the loss of material upon manufacturing, thus providing a better cost advantage in

25   comparison with the sheet wrapping method.

To form the FRP pipe 12 having a layered structure by pultrusion process, the FRP pipe 12 can be overwound but may be preferably provided with twenty or less layers in number. This is because a molded product having layers of more than twenty would make the preparation work considerably complicated, thereby compromising its mass productivity.

The fibers that form the FRP pipe 12 have desirably a low density and a high elasticity in order to provide an increased first-order flexural resonance frequency for the power transmission shaft. Such fibers include PAN-based carbon fibers, pitch-based carbon fibers, silicon carbide fibers, alumina fibers, boron fibers, glass fibers, para-based aramid fibers (such as Kevlar made by DU PONT), and metal fibers (of steel, aluminum alloy, titanium alloy, copper, and tungsten).

It is also possible to employ two or more types of fibers in combination to reduce the cost of the FRP pipe 12. Such fibers as have a high specific elasticity can greatly contribute to the reduction of weight. For example, to use for a power transmission shaft, the PAN-based carbon fibers are preferable in terms of specific strength while the pitch-based carbon fibers are preferable in terms of specific elasticity. From the viewpoint of cost reduction, it is also acceptable to employ a hybrid type of fibers

such as these carbon fibers combined with each other or these carbon fibers combined with glass fibers.

For the PAN-based carbon fibers, the diameter of a fiber is preferably within the range from 1μm to 20μm or

5   more preferably from 5μm to 8μm. For fibers of diameter less than 1μm, acrylic fibers employed as raw material are costly. In addition to this, it is difficult to control the process of forming carbon fibers by carbonization. This in turn increases the cost of the fibers, thus making

10   it difficult to provide shafts at low cost. For fibers of diameter larger than 20μm, it is difficult to provide fibers having a high elasticity. On the other hand, for the pitch-based carbon fibers, mesophasepitch-based carbon fibers are preferably employed which are long fibers and

15   has a high elasticity.

The fibers, which constitute the fiber bundles of the FRP pipe 12 that are spun and aligned in the longitudinal direction, have preferably a tensile elasticity of 196GPa or more, more preferably 245GPa or more. The fibers having

20   a tensile elasticity of less than 196GPa would not sufficiently contribute to the improvement of the cross-sectional second-order moment of inertia of the FRP pipe 12 even when the FRP pipe 12 is increased in thickness because the outer diameter thereof remains unchanged. Accordingly,

25   it is difficult to increase the first-order flexural

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resonance frequency of the power transmission shaft.

Now, consider the tensile elasticity of the fibers
that form the circumferential reinforced fiber sheet 15
provided on the outer and inner surface layers of the FRP

5   pipe 12. It is necessary for the fibers to have a tensile
elasticity sufficiently enough to prevent the
circumferential tensile strain that occurs on a surface of
the FRP pipe 12a having the slit 14, the surface being
opposite to the slit with respect to the center of the pipe,

10   when the FRP pipe 12a is reduced in diameter. In this
context, it is desirable for the fibers that form the
circumferential reinforced fiber sheet 15 to have a high
tensile elasticity of at least 58.8GPa. Such fibers
include the PAN-based carbon fibers, pitch-based carbon

15   fibers, glass fibers, and aramid fibers.

The circumferential reinforced fiber sheet 15 may
take the form such as of a randomly chopped mat or a
continuously strand mat. On the other hand, the
circumferential reinforced fiber sheet 15 requires the

20   basis weight (FAW) within the range from $100g/m^2$ to 600
g/m^2, or preferably from 200 g/m^2 to 400 g/m^2. In addition
to this, the circumferential reinforced fiber sheet 15 also
requires a thickness within the range from 0.05mm to 1.0mm,
or preferably from 0.1mm to 0.8mm.

25   For the fiber sheet 15 of the basis weight (FAW) less

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than 100g/m^2 or of thickness less than 0.05mm, it may be difficult to form a piece of continuous fiber sheet 15 by pultrusion process due to a fracture caused by a tensile force. A piece of fiber sheet 15 of the basis weight (FAW) more than 600g/m^2 tends to become wrinkled upon its formation by pultrusion process. On the other hand, for a piece of fiber sheet 15 of thickness greater than 1.0mm, it is difficult to continuously accommodate the fiber sheet 15 in the outer or inner mold upon its formation by pultrusion process.

No restriction is imposed on the arrangement of the circumferential reinforced fiber sheet 15 of the FRP pipe 12 and any arrangement is acceptable. In other words, the fiber sheet 15 needs not always to be provided on both the outer and inner surface layers. That is, the fiber sheet 15 may be disposed on either the outer surface layer or the inner surface layer, or only on the vicinity of a surface opposite to the slit with respect to the center of the pipe, as long as the fiber sheet 15 can substantially prevent the occurrence of cracks.

Incidentally, instead of the circumferential reinforced fiber sheet 15 provided on the outer and inner surface layers of the FRP pipe 12, the filament winding of reinforcement fibers such as glass fibers is also acceptable which is formed at a certain angle to the

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longitudinal direction at the same time of the formation or after the pultrusion process. However, the filament winding employed together with the pultrusion process would require a special apparatus and thus affect productivity.

5   Accordingly, it is advantageous to use the circumferential reinforced fiber sheet 15.

It is also possible to fix the FRP pipe 12 to the metal pipe 11 with adhesive. When a pipe is press-fitted into another, both pipes having a simple cylindrical shape,

10   the adhesive may be removed upon press-fitting. Accordingly, there may be left no adhesive between the inner circumference of the metal pipe 11 and the outer circumference of the FRP pipe 12.

As shown in Figs. 5a to 5c, to overcome this problem,

15   on the outer circumference of the FRP pipe 12c are provided axial grooves 16 serving as an adhesive-retaining recessed portion between the metal pipe 11 and FRP pipe 12c after having been assembled. Such adhesive-retaining recessed portions include other structures such as circumferential

20   grooves 16a (see Fig. 6a) and recessed portions 16b (see Fig. 6b). Alternatively, as shown in Figs. 7a to 7d, such circumferential grooves 16c as will serve as an adhesive-retaining recessed portion after assembly may be formed plastically in advance on the inner circumferential surface

25   of a metal pipe 11a.

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In general, no restriction is imposed on the adhesive
to be used as long as the adhesive can bond metal and FRP
together. For example, all the metal-FRP adhesives can be
used which are described in "Science and Reality of
Adhesive" published by Kabushiki Kaisha Kobunshi, and "How
to Select Adhesive for High Performance" published
Kabushiki Kaisha Gijutsu Hyoronsha. More desirable
adhesives include a structural adhesive which is an epoxy-
based adhesive of a solution type containing aluminum
powder or iron oxide powder and which enables resistance
welding which is typified by spot welding. To correct the
balance of the shaft later in its manufacturing process,
this weldable adhesive allows balance pieces to be welded
onto the shaft without any problem. To cure adhesive, the
heat can be used which is applied to the outer
circumference of the metal pipe for painting by
carbonization.

No particular restriction is imposed on thermosetting
resin to be used as a matrix for the FRP pipe 12. In
general, it is possible to use thermosetting resins such as
epoxy resin, phenol resin, unsaturated polyester resin,
vinyl ester resin of bisphenol A type or novolak type,
urethane resin, alkyd resin, xylene resin, melamine resin,
furan resin, silicon resin, and polyimide resin. In terms
of strength, it is preferable to use the epoxy resin or

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vinyl ester resin.

To use the epoxy resin for the matrix, the resistance to heat of the epoxy resin after having been cured may be 60℃ or more in terms of the glass transition temperature, preferably 80℃ or more. For the power transmission shaft of a vehicle in which the ambient temperature is on the order of 60℃, an epoxy resin having a resistance to heat of less than 60℃ after having been cured may cause a serious problem, and thereby cannot be used as the matrix.

It is also possible to use a modified epoxy resin which contains rubber particles in an epoxy resin to form a sea-island structure and which is thereby provided with resistance to impact. It is also possible to use a modified epoxy resin having principal chains or side chains modified in chemical structure. In this case, it is possible to provide damping properties for the resulting power transmission shaft. It is also possible to use an epoxy resin which is provided with electrical conductivity by distributing fillers such as electrically conductive carbon black or metal powder in the epoxy resin.

To use the vinyl ester resin for the matrix, the glass transition temperature after it has been cured may be 60℃ or more, preferably 70℃ or more. For the power transmission shaft of a vehicle in which the ambient temperature is on the order of 60℃, a vinyl ester resin

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having a glass transition temperature of less than 60℃

after it has been cured may be reduced in elasticity,

resulting in a drop in flexural rigidity of the FRP pipe 12.

Suppose that an FRP pipe 12 to be used for insertion is

5   manufactured using the vinyl ester resin as the matrix by

pultrusion process.   In this case, an inner mold release

agent can be contained in the resin to improve its

formidability.

To improve the strength of the interface between the

10   matrix and the fibers, a surface of reinforcement fibers to

be used may be subjected to ozone oxidation or ultraviolet

radiation to activate the surface, while a silane coupling

agent or titanium coupling agent may be used for wet

processing to improve affinity.   Alternatively, a highly

15   reactive functional group site may be formed on the surface

of the fibers and then cured together with a thermosetting

matrix resin to thereby provide firm adhesion having a

chemical bond.

No particular restriction is imposed on the type of

20   metal for use with the metal pipe 11 as long as the metal

permits machining such as boring, welding, friction welding,

or press-fitting.   However, preferable metals include iron,

aluminum, copper, titanium, tungsten, and nickel.

Furthermore, an alloy of any of these metals may also be

25   used.

The dimensions of the power transmission shaft made up of the metal pipe 11 and the FRP pipe 12 are determined by the flexural natural frequency required of the power transmission shaft. In other words, to satisfy the necessary flexural natural frequency only with the metal pipe 11, the pipe is to be increased in diameter and weight. For example, to overcome this problem, the thickness of the metal pipe 11 may be designed to satisfy only the necessary static torsional strength, and an FRP pipe 12 having a high elasticity may be inserted into the metal pipe 11 so as to satisfy the flexural natural frequency required for the outer circumference thereof. This makes it possible to reduce the outermost diameter and weight of the shaft.

Such a metal pipe 11 may have a length of 100mm or more and 6000mm or less, preferably 200mm or more and 6000mm or less. For a metal pipe 11 less than 100mm in length and having a diameter which satisfies the required static torsional strength, the metal pipe 11 has already a high rigidity sufficiently enough to eliminate inserting an FRP pipe 12 into the metal pipe 11. For a metal pipe 11 greater than 6000mm in length, it is difficult to install the pipe in a vehicle even when the vehicle is a truck.

It is preferable to determine the axial length of the FRP pipe 12 being inserted into the metal pipe 11 such that the value of FL/PL is within the range from 0.1 to 1.0,

where PL is the length of the metal pipe 11 (see Fig. 1a) and FL is the length of the FRP pipe 12 (see Fig. 1b). With the value of FL/PL being less than 0.1, it is difficult to achieve the necessary flexural rigidity even

5   when an FRP pipe 12 having a high specific elasticity is incorporated into the metal pipe 11. With the value of FL/PL being greater than 1.0, the FRP pipe 12 is longer than the metal pipe 11. That is, this makes it impossible to employ a metal-to-metal joint method appropriately at

10   least on one side of the resulting power transmission shaft.

The metal pipe 11 is preferably within the range from 1mm to 10mm in thickness. A metal pipe 11 having a thickness of 1mm or less may be damaged when carried or the FRP pipe 12 is inserted therein. This also makes it

15   difficult to design the inner diameter and thickness of the metal pipe 11 to satisfy only the static torsional strength required of the power transmission shaft for use with a vehicle. Even when the metal pipe 11 can be designed, the pipe is increased in diameter. A metal pipe 11 of

20   thickness more than 10mm is too heavy to be employed as the shaft for use with a passenger car, thus making it impossible to achieve the object of reducing weight.

The metal pipe 11 has preferably an outer diameter within the range from 10mm to 250mm, preferably from 15mm

25   to 230mm, more preferably from 20mm to 200mm. A metal pipe

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11 having an outer diameter of less than 10mm cannot

satisfactorily transmit the torque required by a passenger

car even with the FRP pipe 12 inserted in the metal pipe 11.

On the other hand, a metal pipe 11 of outer diameter

5 greater than 250mm would raise a space problem that the

pipe interferes with other parts inside the vehicle.

It is also preferable that the value of t_2/t_1 is

within the range of 0.01 to 10, where t_1 is the thickness

of the metal pipe 11 (see Fig. 1a) and t_2 is the thickness

10 of the FRP pipe 12 (see Fig. 1b). With the value of t_2/t_1

being less than 0.01, it is difficult to provide a flexural

rigidity that satisfies the necessary flexural natural

frequency even when an FRP pipe 12 having a high specific

elasticity is incorporated into the metal pipe 11. With

15 the value of t_2/t_1 being greater than 10, an improvement can

be expected in flexural rigidity when the FRP pipe 12 is

incorporated into the metal pipe 11. However, this would

cause the relative amount of FRP being used to increase,

thereby raising a problem of increasing manufacturing costs.

20 The resulting power transmission shaft provided in

this way has sufficient reliability in torsional strength

and joint strength required for a vehicle, being light in

weight and compact. Furthermore, since a metal surface is

available on the outer circumference, it is possible to

25 correct the balance of the shaft or paint the shaft in the

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existing line and process. Furthermore, the power

transmission shaft provides the same performances as those

of the current propeller shaft in terms of resistance to

hitting stones (or resistance to chipping) during running

with passengers in the vehicle and resistance to corrosion

due to salt water. In particular, consider the case where

the FRP pipe is formed by pultrusion process. In this case,

in comparison with the sheet wrapping method, the step of

winding the prepreg sheet, the shrink tape and the step of

winding the shrink tape, and the step of curing prepreg

sheet (or heat treatment) can be eliminated. This makes it

possible to considerably reduce the loss of material upon

manufacturing, thereby realizing the reduction of

manufacturing costs of the power transmission shaft.

Now, examples are explained below as a typical

example in which the power transmission shaft is applied to

as a propeller shaft of a vehicle, however, the present

invention is not limited to these examples. In these

examples, the hammering method was employed to evaluate

flexural rigidity. The first-order flexural natural

frequency of a shaft being supported at both ends, 130Hz or

more, was employed as the passing criterion to judge the

measured values.

In Example 1, the pultrusion process was used to form

an FRP pipe (70mm in outer diameter and 3mm in thickness)

while the tow of PAN-based carbon fibers of elasticity

255kN/mm^2, "PYROFIL TRH50 made by Mitsubishi Rayon Co.,

Ltd.," and a continuous strand mat employing glass fibers

of elasticity 72.3kN/mm^2, "CSM#300 made by Asahi Fiber

Glass Co.," were being impregnated with a vinyl ester resin,

"8250H made by Japan U-Pica Co., Ltd."

The glass fiber sheet 15 was arranged on the outer

and inner surface layers of the FRP pipe 12, while carbon

fibers were spun and aligned in the axial direction. A

slit of 0.8m in length and 9mm in width was provided on the

FRP pipe, which was then elastically deformed in the

circumferential direction. Then, the FRP pipe was inserted

into a steel pipe (of STKM13B, 70mm in outer diameter,

1.4mm in thickness, and 0.9m in length) down to the middle

portion. Then, the FRP pipe with the slit was allowed to

expand in the circumferential direction to be fixed inside

the metal pipe.

Thereafter, a stub shaft was welded to both ends to

prepare an intermediate shaft for the propeller shaft. The

resulting intermediate shaft provided a first-order

flexural natural frequency of 140Hz when measured by the

hammering method with both ends being supported. This

value tells that the propeller shaft can be satisfactorily

employed for practical use.

In Example 2, the pultrusion process was used to form

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an FRP pipe (70mm in outer diameter and 3mm in thickness) while the tow of PAN-based carbon fibers of elasticity 255kN/mm^2, "PYROFIL TRH50 made by Mitsubishi Rayon Co., Ltd.," and a continuous strand mat employing glass fibers of elasticity 72.3kN/mm^2, "CSM#300 made by Asahi Fiber Glass Co.," were being impregnated with a vinyl ester resin, "8250H made by Japan U-Pica Co., Ltd."

The glass fiber sheet was arranged on the outer and inner surface layers of the FRP pipe, while carbon fibers were spun and aligned in the axial direction. A slit of 0.8m in length and 9mm in width was provided on the FRP pipe, which was then elastically deformed in the circumferential direction. Then, the FRP pipe was inserted into a steel pipe (of STKM13B, 70mm in outer diameter, 1.4mm in thickness, and 0.9m in length) down to the middle portion. Then, the FRP pipe was adhered to the metal pipe with an adhesive, "Penguin Cement #1081L made by Sunstar Engineering Inc."

Thereafter, a stub shaft was welded to both ends to prepare an intermediate shaft for the propeller shaft. The resulting intermediate shaft provided a first-order flexural natural frequency of 143Hz when measured by the hammering method with both ends being supported. This value tells that the propeller shaft can be satisfactorily employed for practical use.

In a comparative example, an FRP pipe was spun in the same way as in the aforementioned examples without using the glass fiber sheet. A slit of width 9mm was provided on the FRP pipe, which was then elastically deformed in the

5 circumferential direction. When the FRP pipe was then inserted into the steel pipe, cracks occurred on the surface of the FRP pipe. The cracks prevented the FRP pipe from expanding inside the metal pipe, thereby making it impossible to adhere the FRP pipe to the metal pipe.

10 While there has been described what are at present considered to be preferred embodiments of the invention, it will be understood that various modifications may be made thereto, and it is intended that the appended claims cover all such modifications as fall within the true spirit and

15 scope of the invention.